Evolution in the 21st Century

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Forget what your mother taught you about evolution!

- If she was a Creationist, evolutionary science is far from exhausted.
- If she was a Darwinist who believed everything was basically solved by 1940, then you’re in for some surprises.

Basic issues in evolutionary debates

- Origin of life/the first cells

  - still on the fringes of serious scientific discussion
- Related descent with modification of all living organisms

  - more convincing with each new technological advance (detailed genome phylogenies)
- The actual processes of evolutionary change over time

  - an ever growing number of possibilities as we learn more about how cells manage their genomes

Major Points

- Evolution does not have to proceed by small changes – and we know from the DNA record that major steps did not occur gradually.
- DNA change is a cell-regulated, biological process, not a series of infrequent, random, independent accidents. (Genome as RW memory system)
- There is no conceptual problem in dealing scientifically with complex evolutionary events – or with the evolution of complexity.

Darwin's 1859 gradualist view

If it could be demonstrated that any complex organ existed, which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down. But I can find out no such case. No

Origin of Species, p. 194

Darwin's later acknowledgment of other possibilities:

"...variations which seem to us in our ignorance to arise spontaneously. It appears that I formerly underrated the frequency and value of these latter forms of variation, as leading to permanent modifications of structure independently of natural selection."

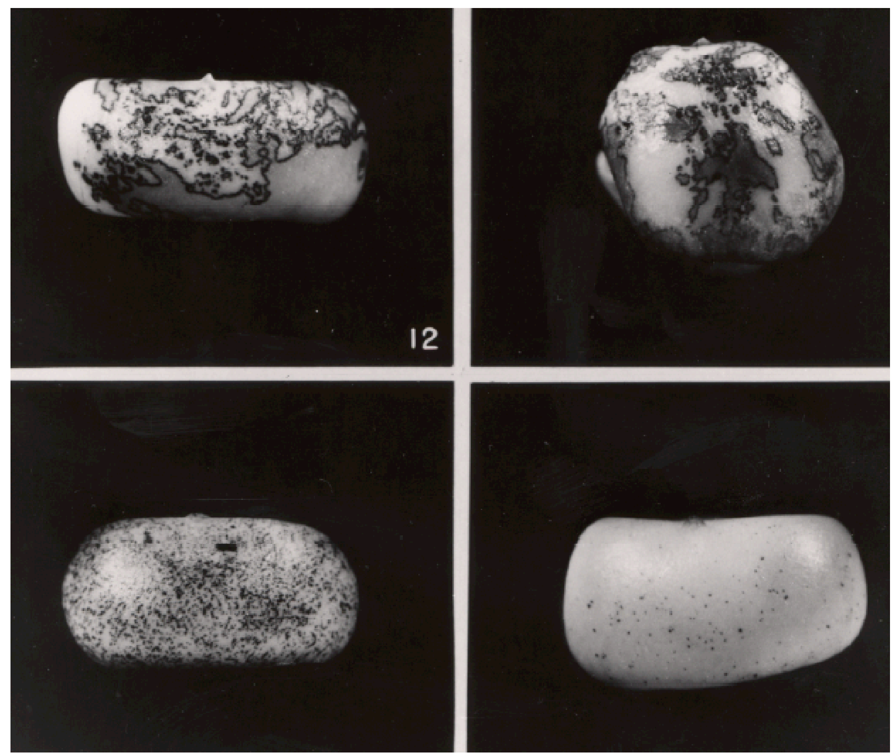
(*Origin of* Species, 6th edition, Chapter XV, p. 395).

Four kinds of rapid, multi-character changes Darwin could not have imagined

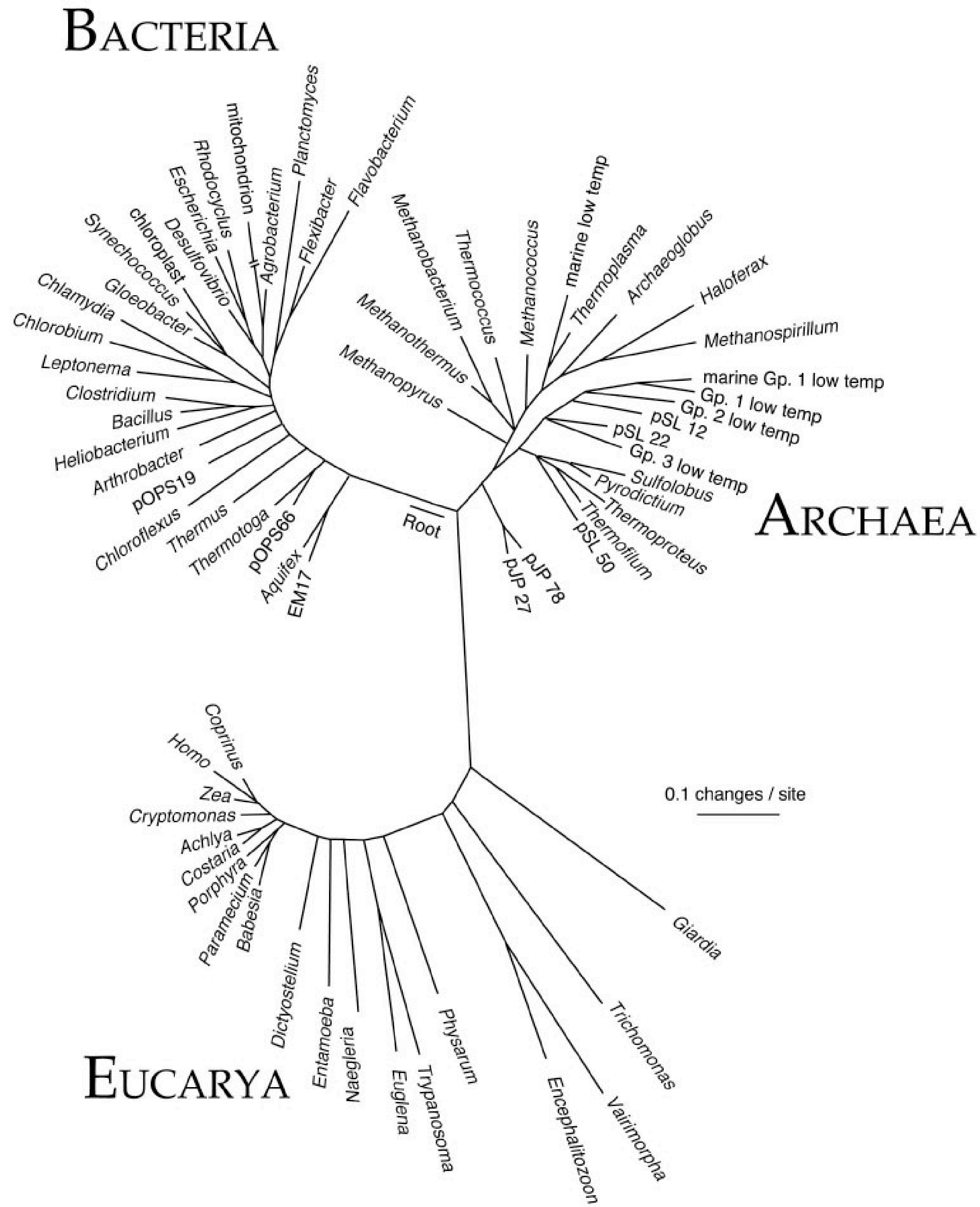
- Multiple cell types and cell fusions in evolution;
- Horizontal DNA transfer in evolution;
- Genome doublings at key steps of eukaryotic evolution;
- Built-in mechanisms of

genetic change = natural genetic engineering

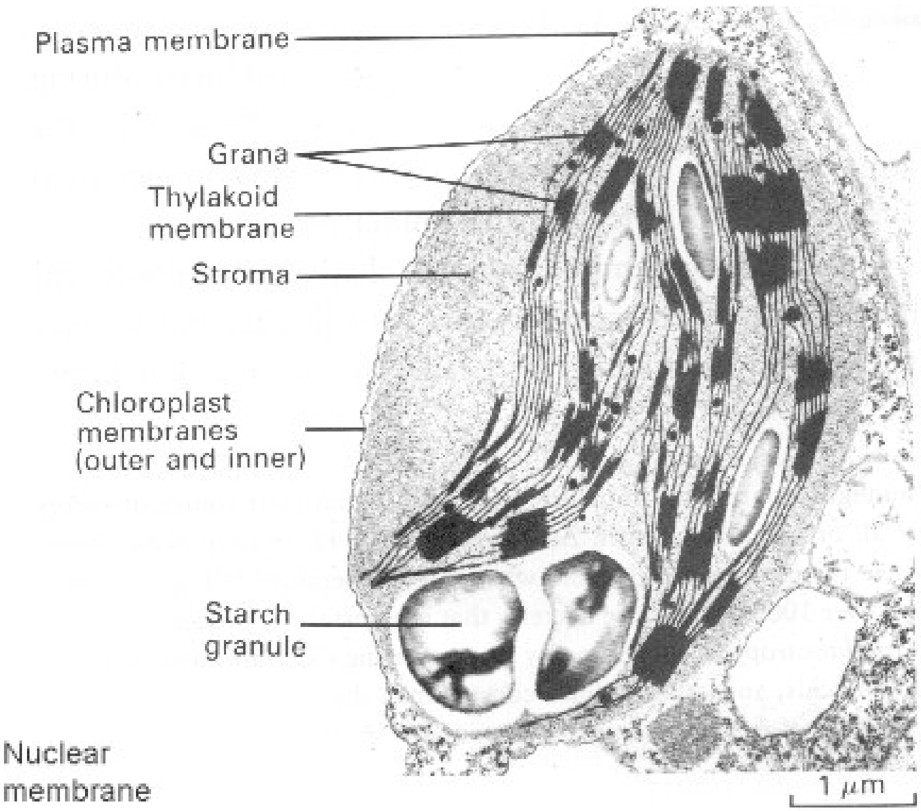
Barbara McClintock, 1951

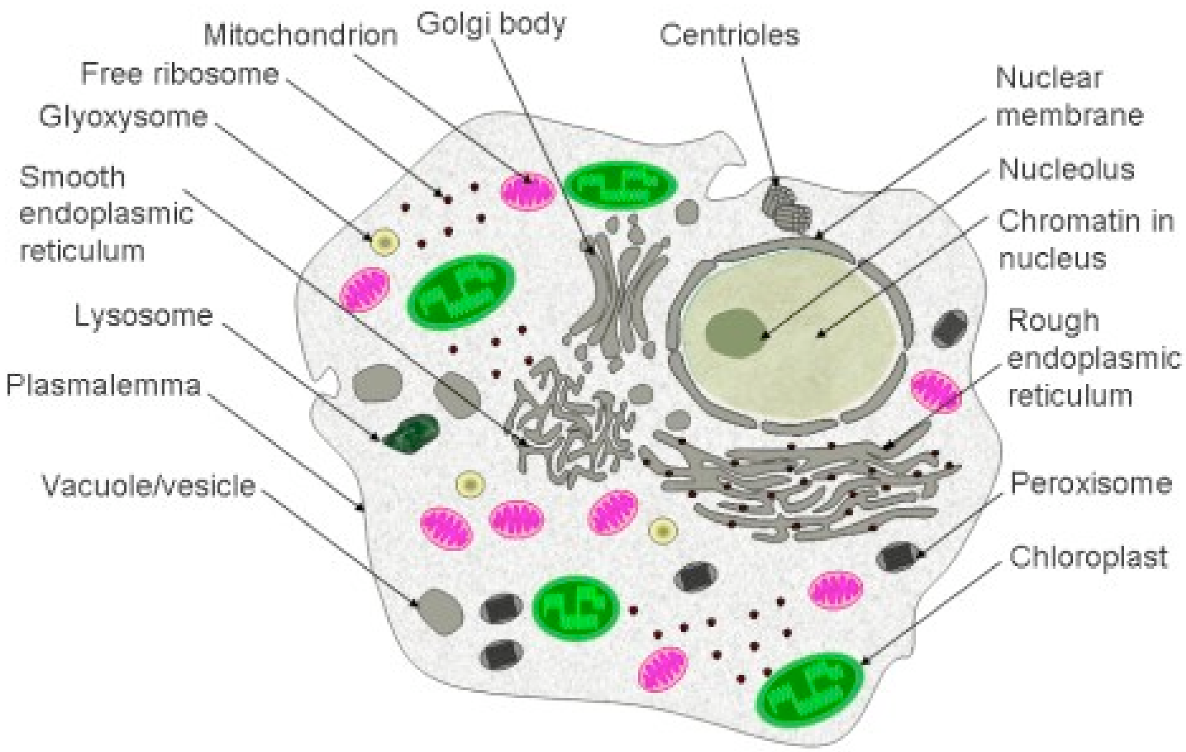


Carl Woese, molecular phylogeny, and three cell kingdoms (1977)

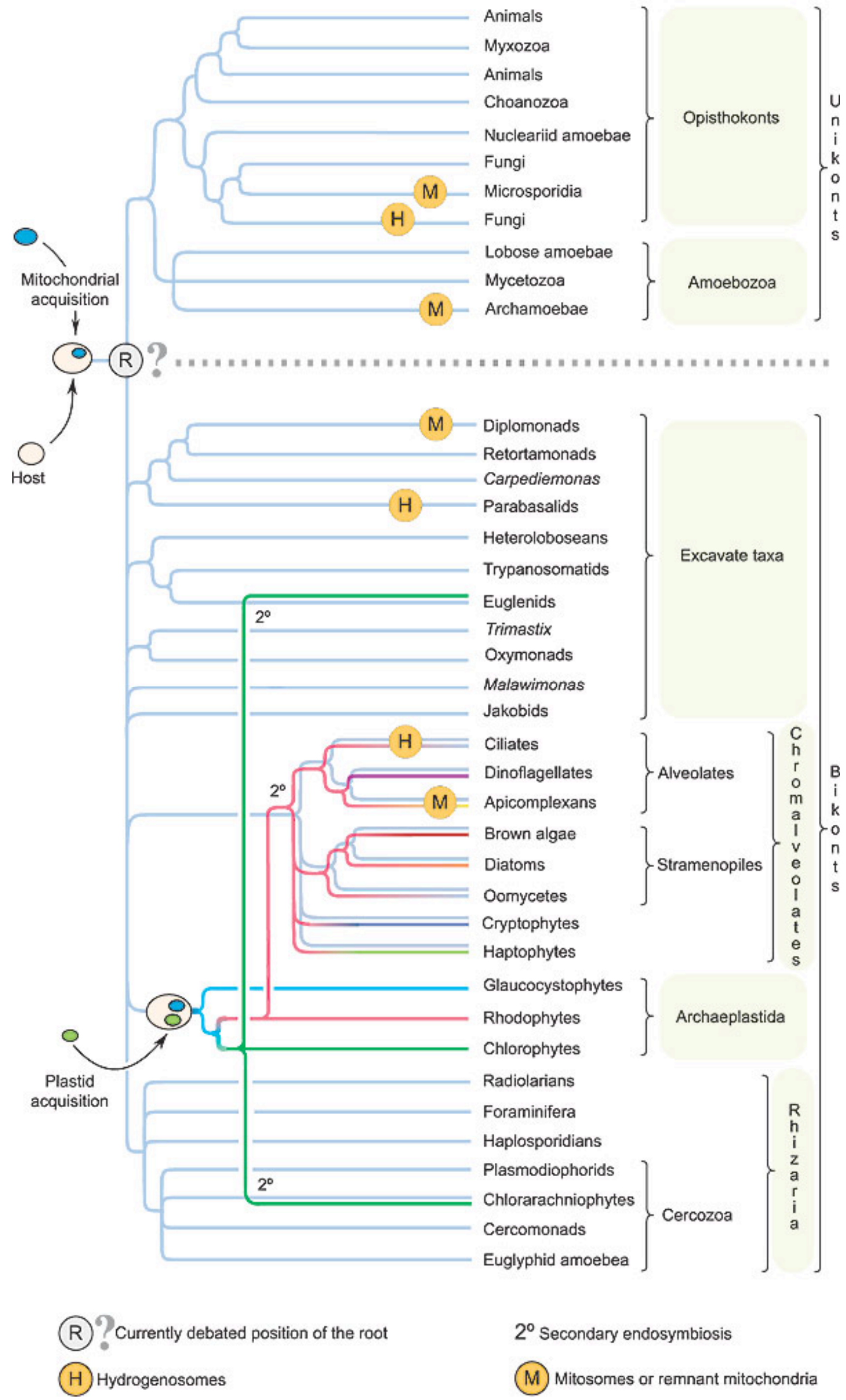


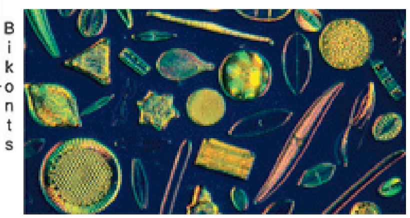
Mitochondria and chloroplasts are endosymbiotic bacteria inside eukaryotic cells





What genomes teach: cell fusions at key places in eukaryotic evolution





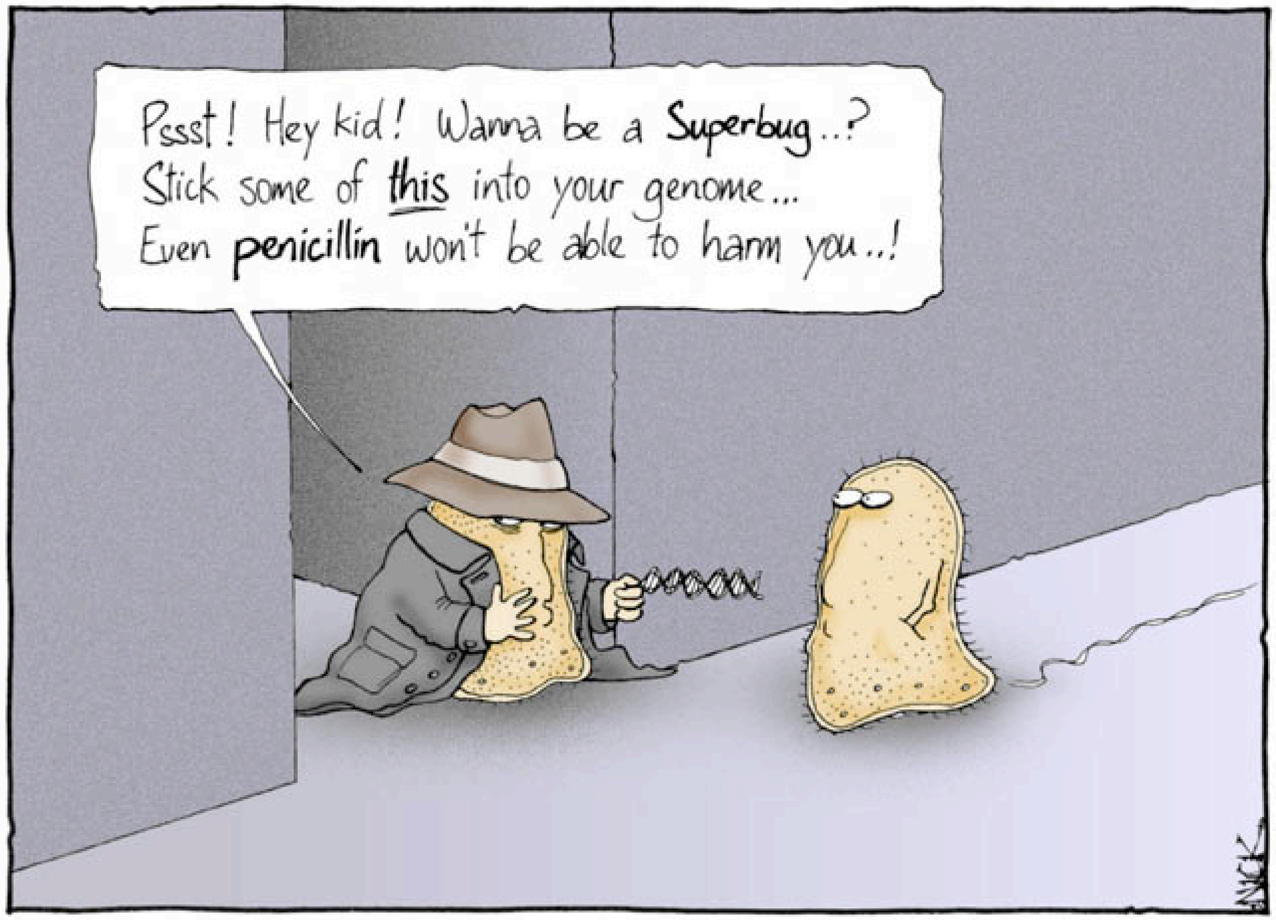
diatoms

T. M. Embley and W. Martin. 2006. Eukaryotic evolution, changes and challenges. Nature 440, 623-630.

Evolution in real time using horizontal DNA transfer: Bacterial antibiotic resistance

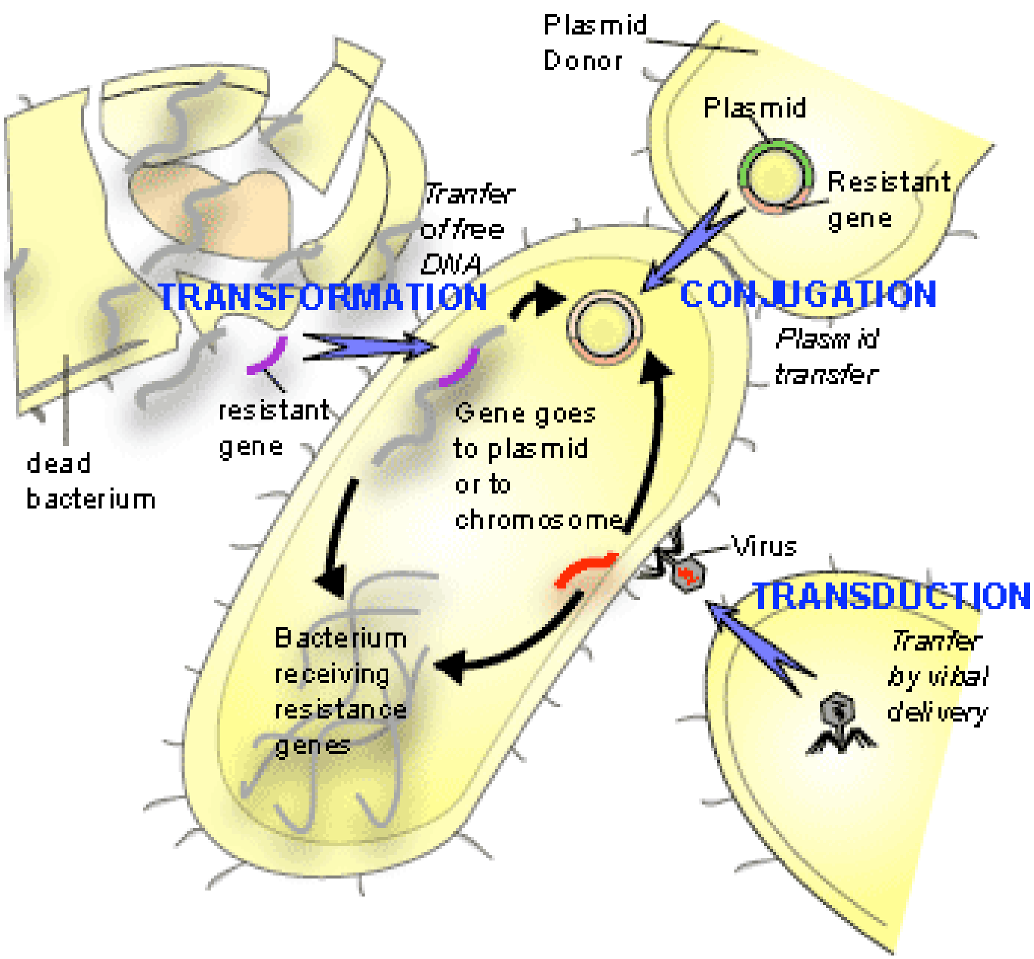
- experimentally confirmed mutation theory of resistance (1950s)

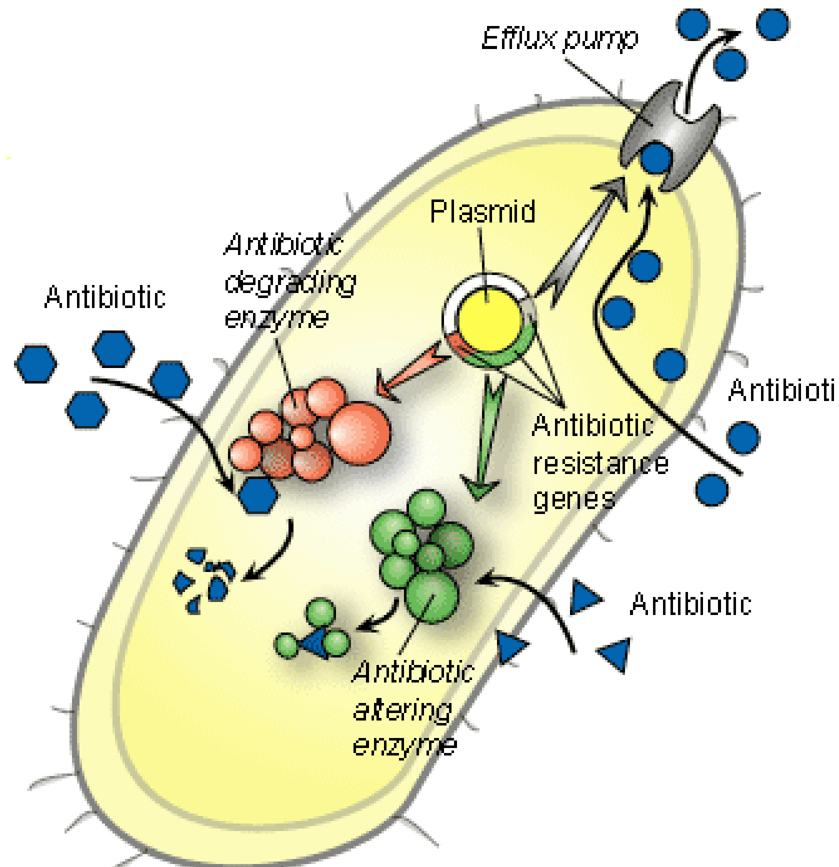
- clinically resistant bacteria carry transmissible plasmids (Watanabe, 1963)



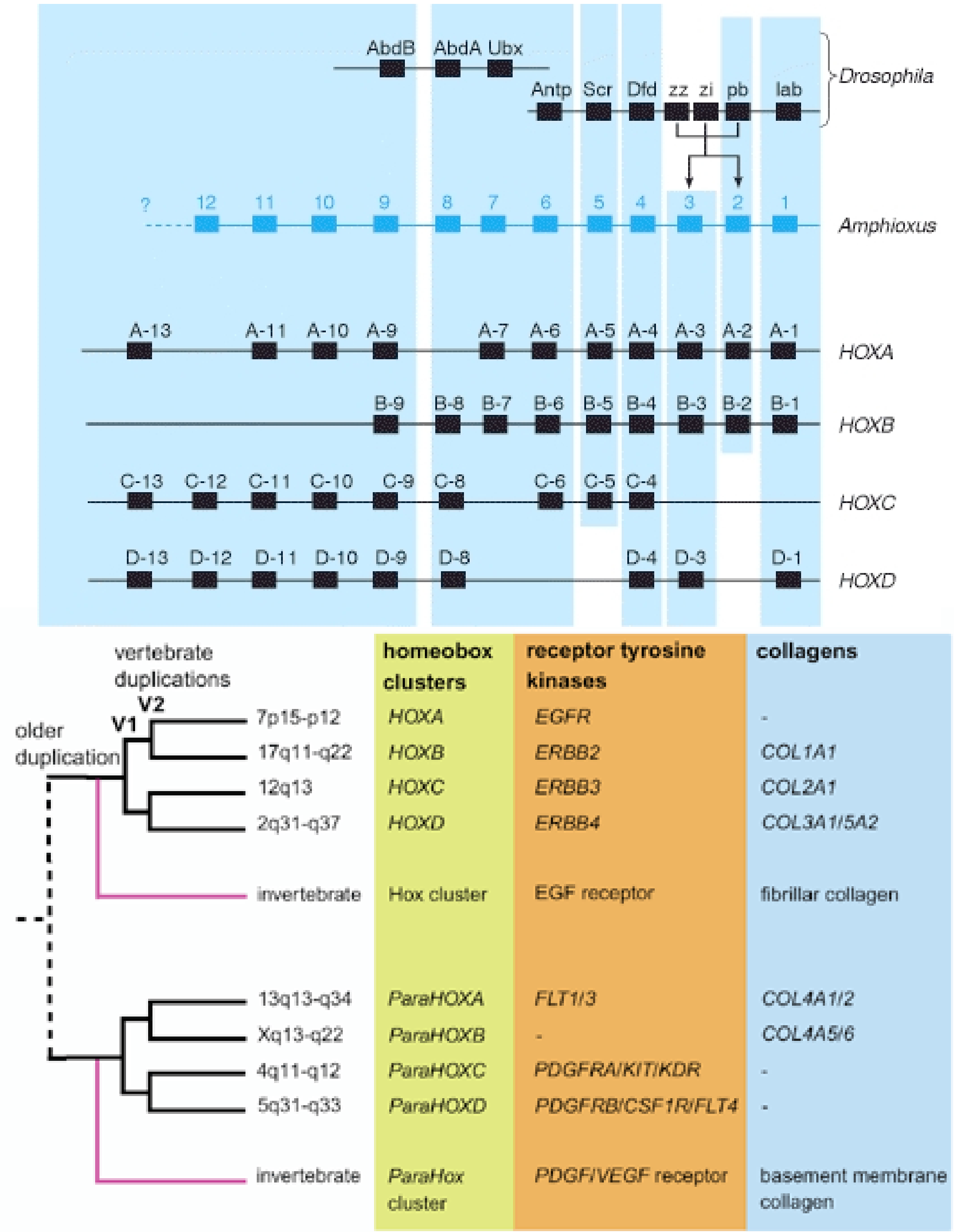
It was on a short-cut through the hospital kitchens that Albert was first approached by a member of the Antibiotic Resistance.

Transmissible Antibiotic Resistance



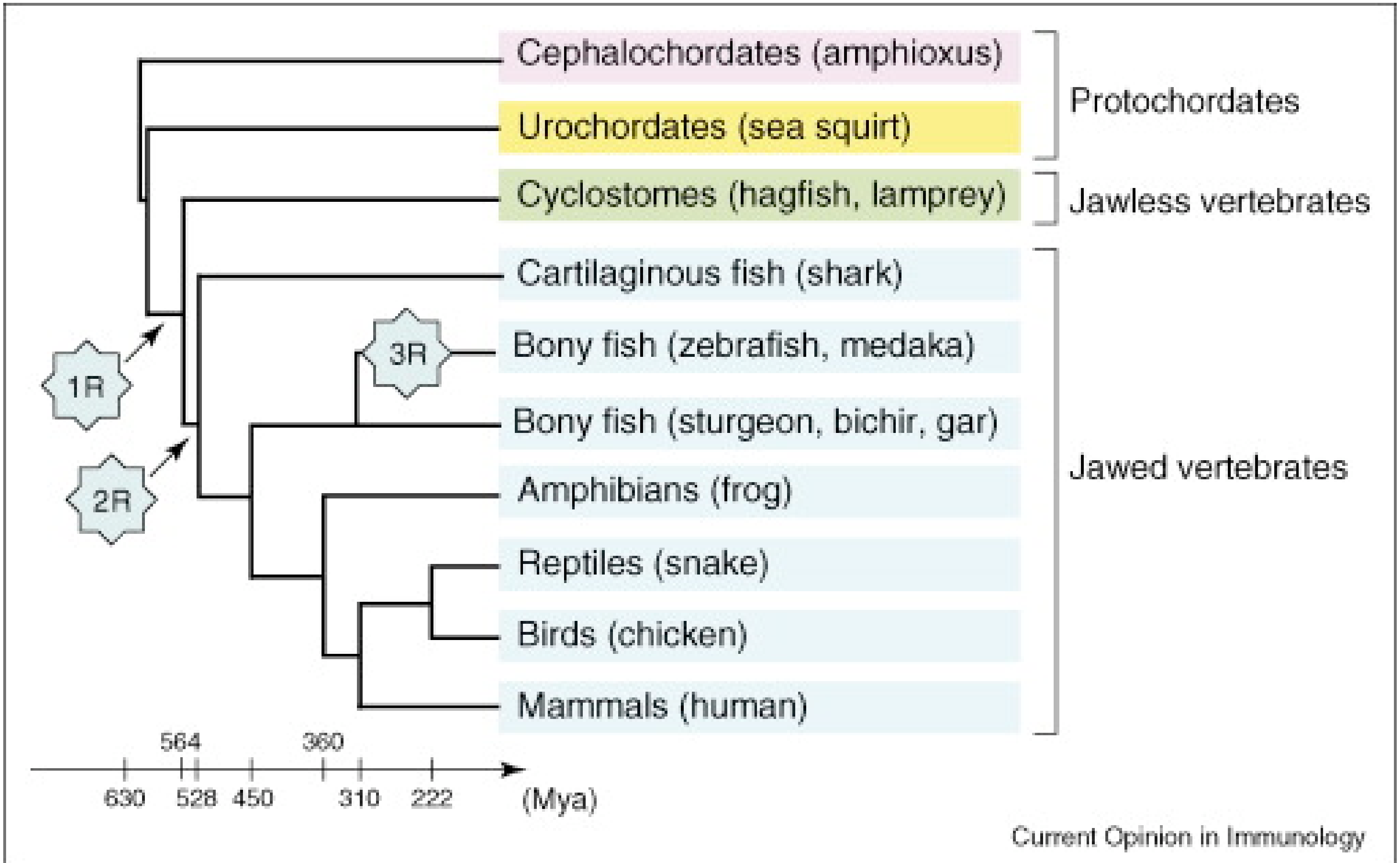


Genomic duplications in vertebrate evolution



•Jurg Spring. **Genome duplication strikes back.** *Nature Genetics* †**31**, 128 - 129 (2002) doi:10.1038/ng0602-128

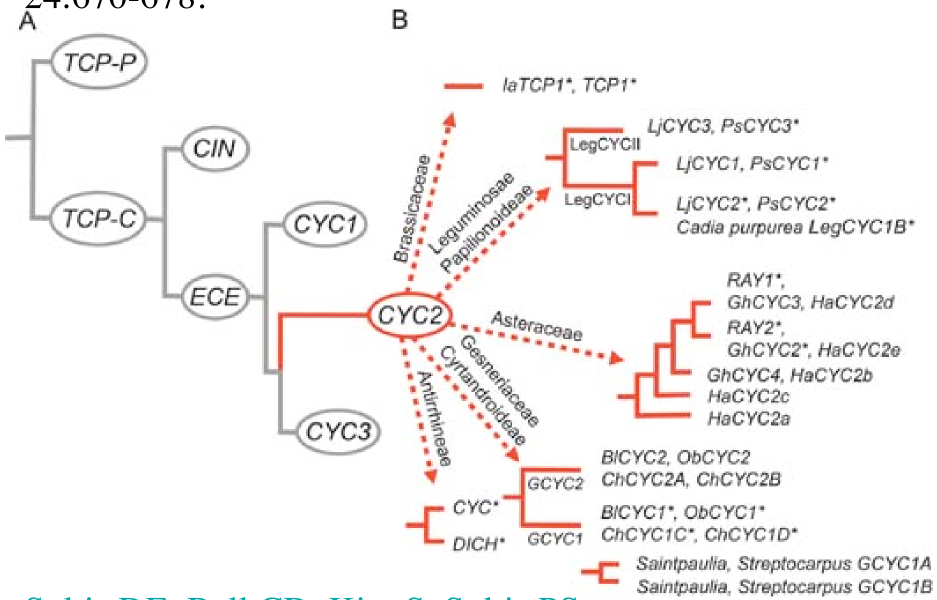
What genomes teach: whole genome duplications at the root of vertebrate evolution



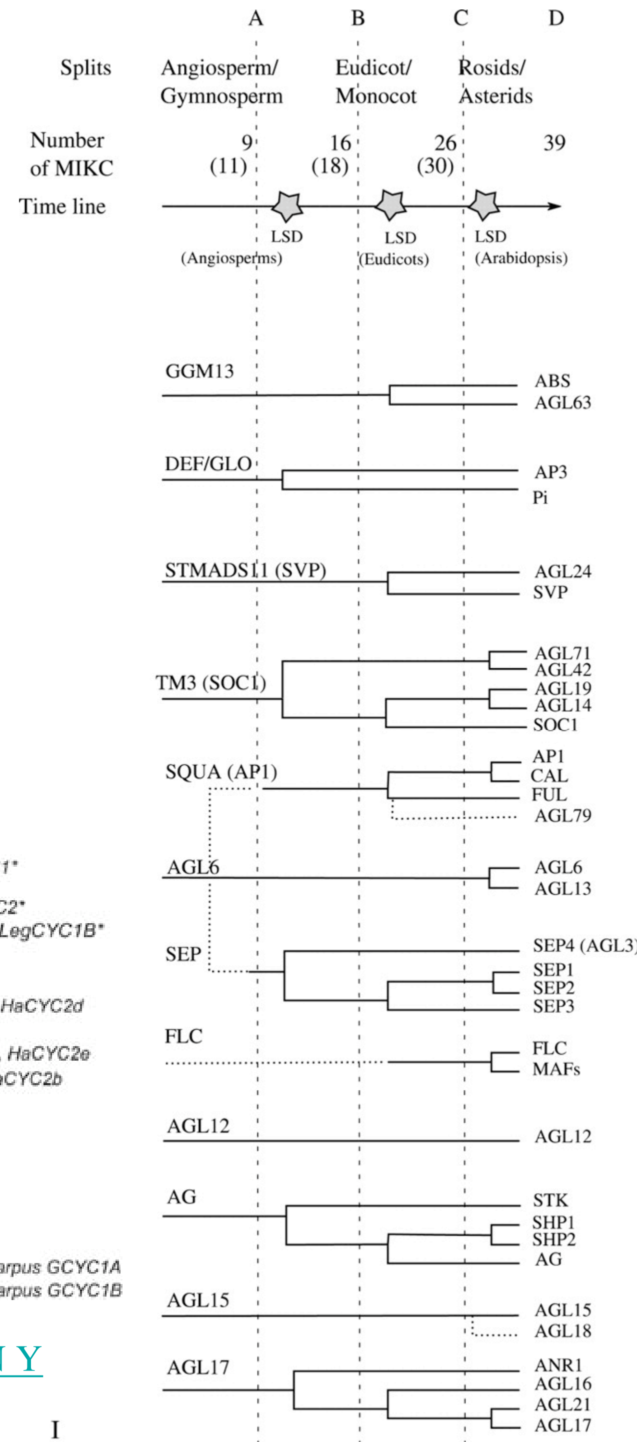
The 2R hypothesis: an update. Kasahara, M. 2007 *Current Opinion in Immunology* 19 (5), pp. 547-552

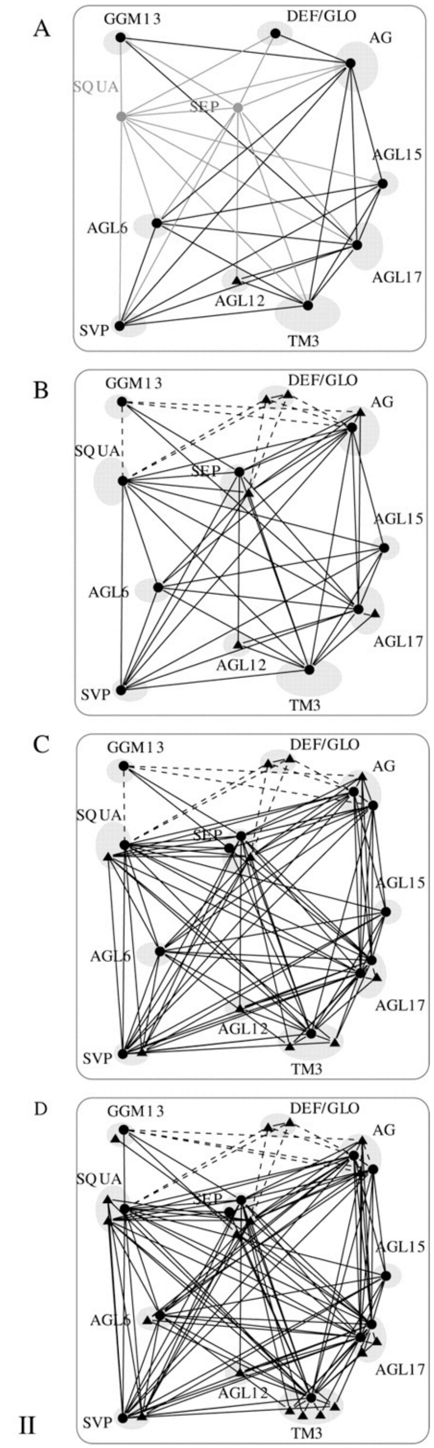
Network Evolution by Whole Genome Duplication

A. S. Veron, K. Kaufmann, and E. Bornberg-Bauer. Evidence of Interaction Network Evolution by Whole-Genome Duplications: A Case Study in MADS-Box Proteins. Mol Biol Evol March 1, 2007 24:670-678.

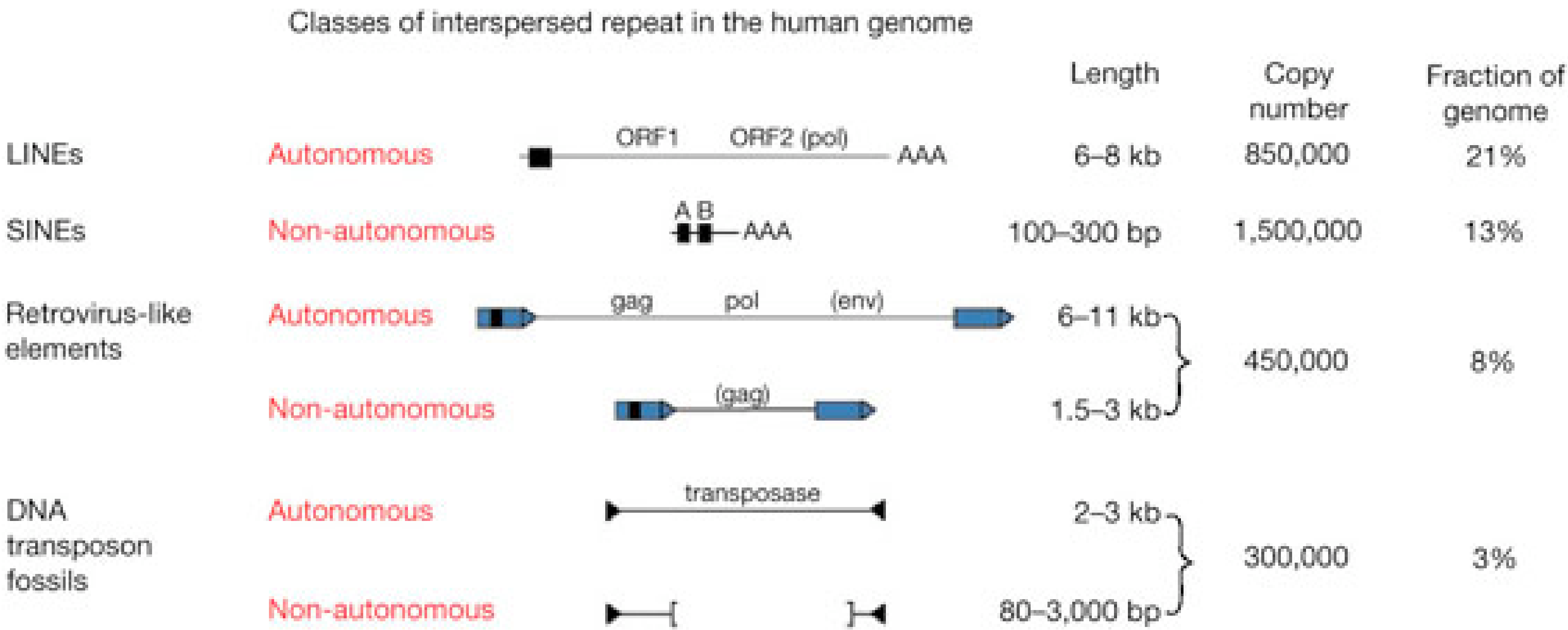


[Soltis DE](), [Bell CD](), [Kim S](), [Soltis PS.]()
Origin and early evolution of angiosperms. [Ann N Y Acad Sci.]() 2008;1133:3-25.





What genomes teach: dispersed repeats in the human genome



International Human Genome Sequencing Consortium. Initial sequencing and analysis of the human genome. Nature 409, 860 - 921 (2001)

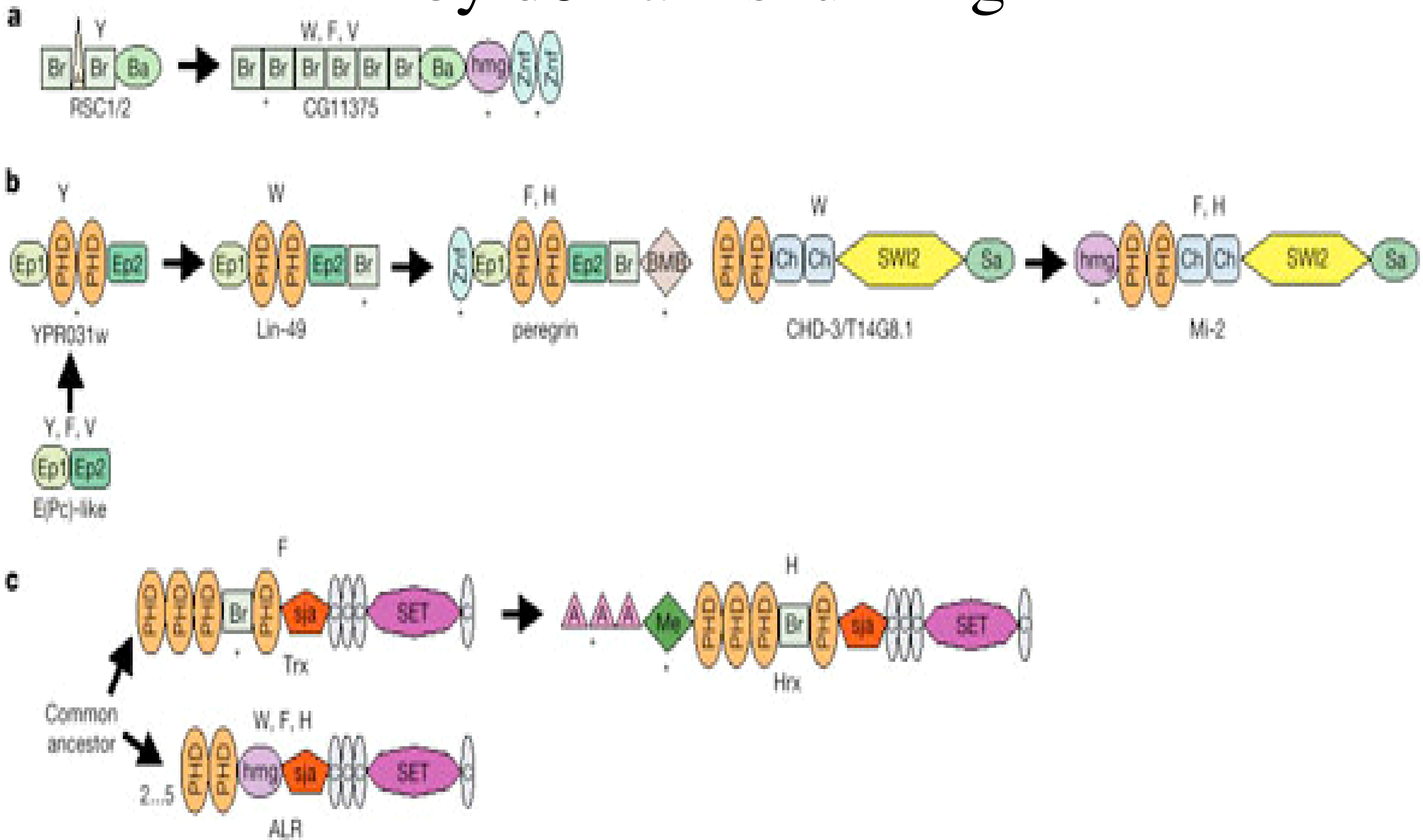
Natural Genetic Engineering

- Nucleotide substitutions by mutator polymerases
- DNA import and export systems
- General and localized recombination systems.
- Mobile DNA elements and large scale genome rearrangements.
- Mobile elements that transpose through RNA intermediates and mobilize shorter genome/RNA segments.
- Direct integration of cellular RNAs into the genome by reverse splicing.

Adaptive use of natural genetic engineering

- Protein switching and engineering by diverse organisms.
- The mammalian immune system as an example of rapid protein evolution and specialization by natural genetic engineering.

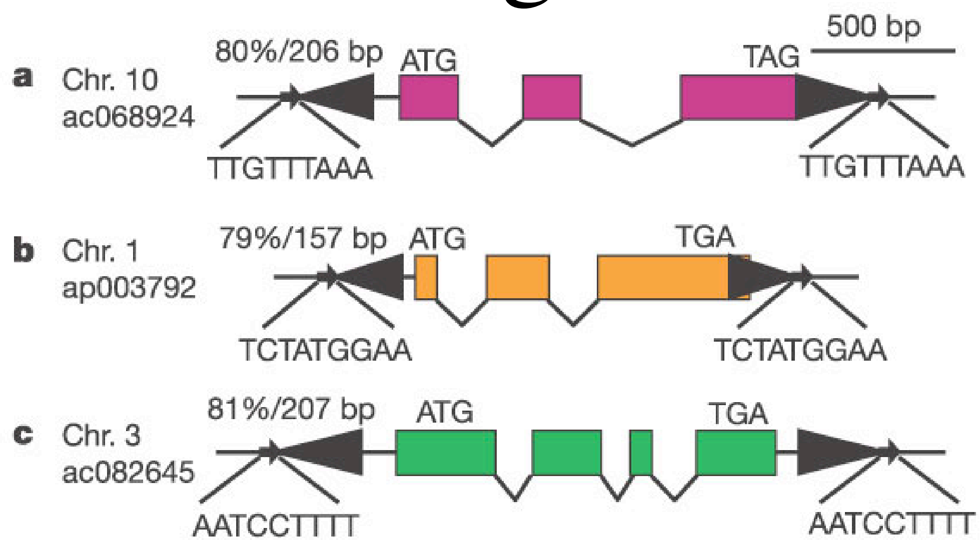
What genomes teach: protein evolution by domain shuffling

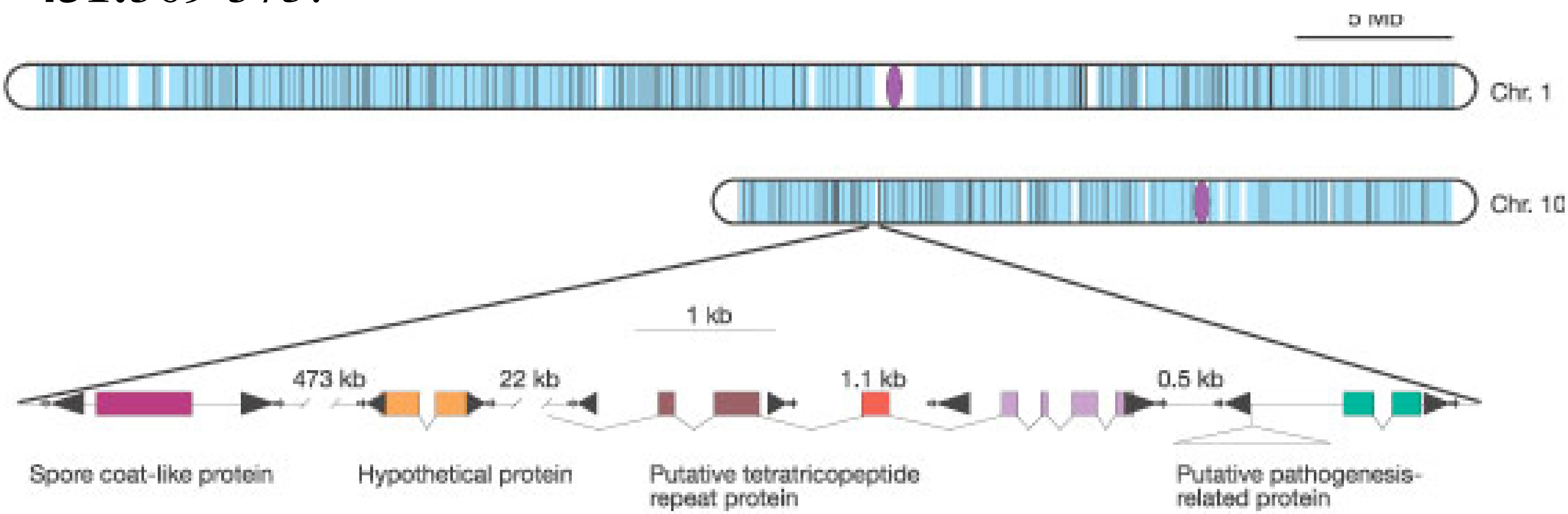


International Human Genome Sequencing Consortium. Initial sequencing and analysis of the human genome. Nature 409, 860 - 921 (2001)

Natural genetic engineering in evolution: Pack MULEs in the rice genome

Jiang N, Bao Z, Zhang X, Eddy SR, Wessler SR: **Pack-MULE transposable elements mediate gene evolution in plants.** *Nature* 2004, **431:**569-573.

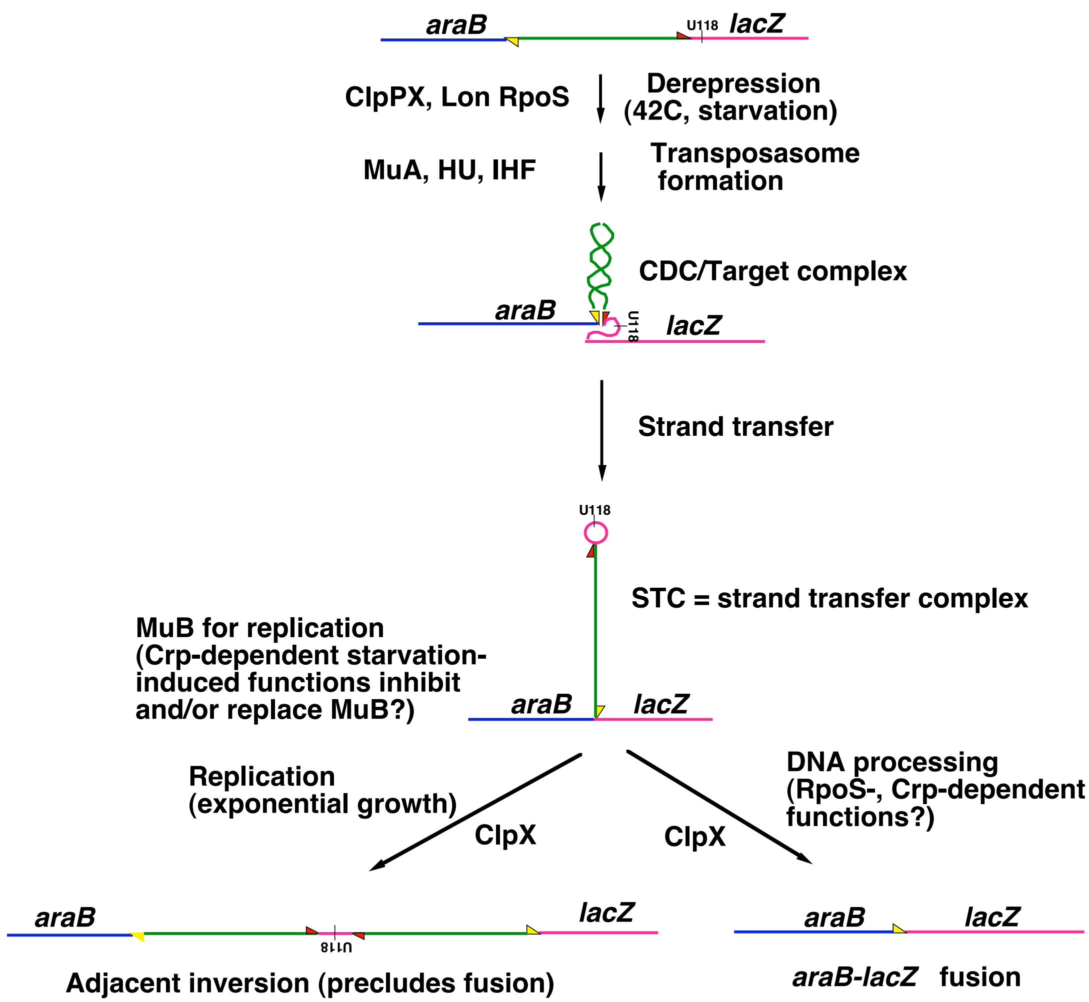


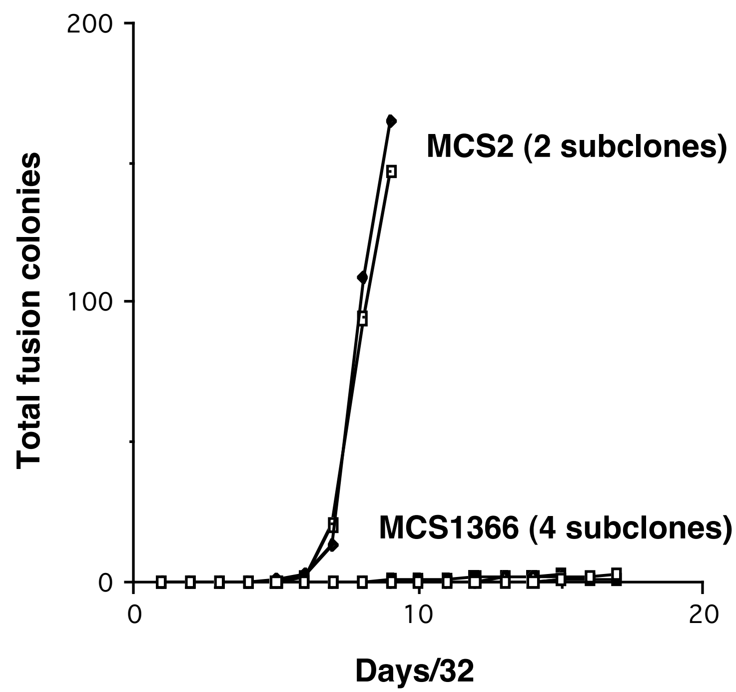


Stimuli that Activate Natural Genetic Engineering

- Chromosome breaks (McClintock, 1944)
- Pheromones, hormones & cytokines
- **Starvation** (Shapiro, 1984)
- DNA damage (mutagens)
- Telomere erosion
- Antibiotics, Phenolics, Osmolites
- Oxidants
- Pressure, Temperature, Wounding
- Protoplasting & growth in tissue culture
- **Bacterial or fungal infection & endosymbiosis**
- **Changes in ploidy & DNA content (genome doubling)**
- **Hybridization (interspecific mating)**

Temporal & metabolic regulation of natural genetic engineering





Shapiro, J.A. 1997b. Genome organization, natural genetic engineering, and adaptive mutation. *Trends in Genetics* **13**, 98-104

21st Century view of evolutionary change: the importance of a cognitive systems perspective

- McClintock (1984): “In the future, attention undoubtedly will be centered on the genome, with greater appreciation of its significance as a highly sensitive organ of the cell that monitors genomic activities and corrects common errors, senses unusual and unexpected events, and responds to them, often by restructuring the genome.”
- Ecological events and subsequent biological challenges activate natural genetic engineering functions that can act at multiple genomic locations within one or a few generations
- Molecular basis for rapid genome restructuring affecting multiple adaptive features at the same time in response to abrupt challenges

Searching Genome Space by Natural Genetic Engineering: More Efficient than a Random Walk Guided by Gradual Selection

- combinatoric search using established functional modules (e.g. domain accretion and shuffling)
- activation when most biologically useful by "genome shock" (including starvation, infection, **hybridization**) ==> coordinated changes
- network adaptation after WGD, domain shuffling, establishment of novel interaction patterns
- molecular mechanisms for targeting coincident changes to functionally related locations (agenda for the coming decades)

21^{st} Century view of evolutionary change: a generalized scenario

- Ecological disruption ==> changes in biota, food sources, adaptive needs & organismal behavior;
- Macroevolution triggered by cell fusions & interspecific hybridizations (WGDs) leading to massive episodes of horizontal transfer, genome rearrangements;
- Establishment of new cellular and genome system architectures; complex novelties arising from WGD and network exaptation;
- Survival and proliferation of organisms with useful adaptive traits in depleted ecology; elimination of non-functional architectures; selection largely purifying;
- Microevolution by localized natural genetic engineering after ecological niches occupied (immune system model).